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Development of the Long Valley rhyolitic magma system: Strontium and neodymium isotope evidence from glasses and individual phenocrysts

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Abstract—Pre-caldera high-silica rhyolites of Glass Mountain and the voluminous, zoned rhyolitic Bishop Tuff record the evolution of a magma system from initiation at 2.1 Ma to 0.76 Ma. Pre-1.2 Ma Glass Mountain lavas formed rapidly in two differentiation events recorded by regionally controlled Rb-Sr isochrons at ~2.1 and 1.9 Ma. Younger, post-1.2 Ma Glass Mountain lavas have Nd isotope ratios distinct from the older Glass Mountain lavas and also define two regionally controlled Rb-Sr isochrons, 1.09 ± 0.03 Ma and 1.15 ± 0.01 Ma, that have distinct initial ratios: 0.7057 ± 1 and 0.7060 ± 1 , respectively. These lavas have eruption ages as young as 0.79 Ma and therefore provide evidence of magma residence times of up to 360 kyr, comparable to that recorded in the older Glass Mountain lavas. Neodymium isotope compositions of sanidine and plagioclase from the younger Glass Mountain lavas and late erupted Bishop Tuff are within error ($\epsilon_{Nd} - 1$). Sanidine and plagioclase from the younger Glass Mountain lavas yield glass-mineral Rb-Sr isotope ages close to those of the younger regional isochrons, the exception being feldspar rims which yield ages close to the time of lava eruption. This suggests that feldspar phenocrysts were stored in the magma chamber for up to 300 kyr with little mineral growth until close to the time of eruption when minerals rims were formed. In contrast, feldspars from the early Bishop Tuff form two populations with Sr-Nd isotope systematics implying derivation from magmas that formed the older and younger Glass Mountain lavas. Feldspar rims give ages close to Bishop Tuff eruption. Strontium elemental and isotope zonation suggest that the feldspar populations from the Bishop Tuff represent xenocrytic material that may have resided in the Long Valley magma chamber(s) for up to 1.3 Myr prior to eruption of the Bishop Tuff. Copyright © 1998 Elsevier Science Ltd

1. INTRODUCTION

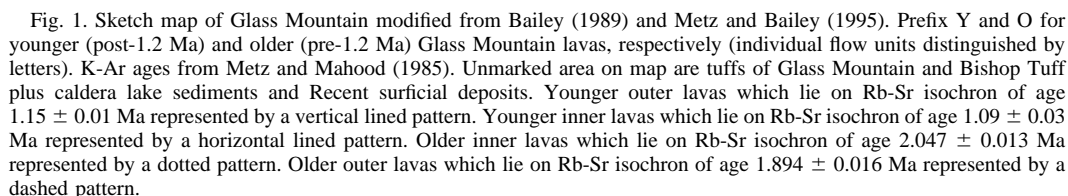
Studies of the Long Valley high-silica magmatic system (LVHMS) in California have been responsible for the introduction and discussion of several important concepts concerning the eruption and formation of compositionally zoned magmas (e.g., Gilbert, 1938; Hildreth, 1979; Michael 1983; Hildreth and Mahood, 1986; Gardner et al., 1991). Most recently, a debate about the rate of magma production, storage, and possible modification of large silicic magma bodies was initiated principally as a consequence of studies on the Long Valley system (Halliday et al., 1989; Sparks et al., 1991; Mahood, 1991; Lu et al., 1992; Hervig and Dunbar, 1992; Davies et al., 1994; Duffield et al., 1995). The interpretation of Sr and Ar isotope data for samples from LVHMS has proved particularly controversial. Glass Mountain lavas appear to have formed from at least four magma batches which were periodically tapped but remained molten for $>10^5$ years (Halliday et al., 1989; Davies et al., 1994). In a similar manner the Bishop Tuff contains minerals which appear to have been in the magma chamber for $>10^5$ yr (Christensen and DePaolo, 1993; Christensen and Halliday, 1996) or even $>10^6$ yr (van den Bogaard and Schirnick, 1995). There has, however, been considerable debate regarding the suggestion that high-silica magmas are kept molten at shallow-crustal levels over such protracted periods (Halliday et al., 1989; Sparks et al., 1991;

Halliday 1991; Mahood, 1991; Christensen and DePaolo, 1993; Davies et al., 1994; Christensen and Halliday, 1996). This debate has introduced the concept of a partially to completely crystallized rind around a magma body that potentially can supply mineral grains to the active magma body should thermal or physical conditions change (Mahood, 1991). Despite continued debate this concept is gaining acceptance (e.g., Nakada et al., 1994).

A recently published re-interpretation of the Bishop Tuff stratigraphy demands that existing data and petrogenetic models be re-assessed (Wilson and Hildreth, 1997). In this paper we provide new Sr-Nd isotope evidence bearing on the evolution of LVHMS. Our aim is to use these and existing data to determine the rate of magma formation, the timescale of magma storage, and the principal petrogenetic processes that contributed to the formation of the LVHMS that culminated in the eruption of ~ 800 km³ of the Bishop Tuff.

Between initiation of LVHMS at ~ 2.1 Ma and the cataclysmic eruption of the Bishop Tuff at 0.76 Ma (Hildreth, 1979, 1981; Pringle et al., 1992) more than fifty high-silica rhyolite flows erupted to produce Glass Mountain on the northeastern side of the caldera (Metz and Mahood, 1985, 1991; Fig. 1). Full details of the petrology and mineral chemistry of all the rock types in the LVHMS can be obtained from cited references and only the most salient points are summarized here. The Glass Mountain lavas generally contain less than 5% phenocrysts (Metz and Mahood, 1991). The lavas are characterized by extreme chemical compositions and their formation included extensive feldspar fractionation that resulted in Sr contents as low as 0.1 ppm (Halliday et al., 1989; Davies et al.,

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Wilson and Hildreth (1997) recently reported an extensive petrological and field study in which they radically re-interpreted the stratig-

In the new stratigraphy, the Bishop fall deposit is now subdivided into nine units, the first eight of which formed within ~100 h with no noticeable depositional hiatus. Unit 9 followed after a possible time break. Early ignimbrites (Ig1) are wholly intraplinian and contain no pyroxene and few/no Glass Mountain derived lithics (Ig1E; Gorges lobe: Ig1SW; San Joaquin lower unit). Later ignimbrites (Ig2), containing pyroxene and Glass Mountain derived lithics, formed at least partially intraplinian and are believed to have formed within a further ~35 h. The vent location for the plinian fall and initial ignimbrite was located in the south-central part of the caldera. Subsequently, the vent

position changed. The initial south-central vent migrated north and east towards Glass Mountain and produced the south and easterly emplaced ignimbrite lobes (Ig2E; Tableland). A second vent opened from west to east along the northern caldera margin producing the northerly emplaced lobes (Ig2NW; Mono lobes: Ig2N; Abobe lobes). The vent position of the southwestern ignimbrites (Ig1SW; San Joaquin lower and Ig2 SW; San Joaquin upper) is unknown. Two significant time markers are recognised in the section: (1) the first occurrence of rhyolitic lithics derived from Glass Mountain and pyroxene bearing pumices and (2) the first appearance of recycled intracaldera ignimbrite containing rhyolite lithics.

This new interpretation concludes that much of the Bishop ignimbrite is intraplinian and that fall and ignimbrite deposits are not formed in the sequential manner as previously proposed. Samples on which isotopic data have previously been reported can be subdivided into two: pre and post the second ignimbrite units (i.e., pre and post the first time marker). The first group therefore includes all data reported from air fall deposits, excluding the uppermost fall unit, and Gorges, Chidago, and the lower San Joaquin ignimbrite lobes (i.e., all data from van den Bogaard and Schirnack, 1995). With the exception of two samples discussed by Christensen and Halliday (1996) all other isotopic data are from fall deposits and Ig2 ignimbrites, i.e., relatively early and late in the eruptive sequence. Consequently previous interpretations that ascribed geochemical variations to temporal changes in eruption composition may need to be re-assessed (Wilson and Hildreth, 1997).

2.2. Sampling

The low Sr contents of the early Bishop Tuff and Glass Mountain lavas renders their Sr isotope systematics highly susceptible to alteration, a point emphasized in the first combined Sr-Nd-O isotope study of the Bishop Tuff by Halliday et al. (1984). Samples analysed in this present study of the Young Glass Mountain lavas (YGML) are confined to hand-picked glass from petrographically unaltered vitrophyres. The Bishop Tuff was sampled from the basal plinian air-fall deposit (Chalfant/Bishop Quarry, north of Bishop) and the late Mono ignimbrite lobe (Ig2NW sampled from Aeolian Buttes). It is impossible to unequivocally assess whether the glass samples from the Bishop Tuff were pristine but samples were chosen on the basis of thin section study and fragments with no visible evidence of alteration were selected during hand-picking.

Sanidine (Or_{55-65}) and plagioclase (An_{11-22}) were concentrated from crushed samples using bromoform prior to hand-picking (see Davies et al., 1994, for details). Euhedral feldspars throughout the Bishop Tuff and Glass Mountain lavas are characterized by poorly crystalline overgrowths (Davies et al., 1994). These overgrowths, which have been analysed separately, generally detach during crushing and are not included in the bulk and single grain analyses reported below. The mineralogy of both the Bishop Tuff and Glass Mountain lavas includes a small (<0.1%) but variable population of xenocrystic material, easily distinguished from the euhedral unaltered phenocryst population on the basis of morphology and colour. As in the study of the Older Glass Mountain lavas (Davies et al., 1994) this material has been avoided during hand picking.

Strontium and neodymium isotope analyses were performed on hand picked glasses, and bulk and single feldspar grains from two YGML and two Bishop Tuff samples (LV-8 an early airfall and LV-3 from near the base of the Ig2 NW Mono Ignimbrite lobe). Isotope analyses of single feldspars were confined to the largest grains in each sample (>5 mm). The isotopic composition of feldspar cores and rims were obtained from polished grain mounts. Unfortunately the low Sr abundances precluded the analysis of core and rim from single grains. The core and rim isotopic ratios reported in Table 2 and 3 represent ~0.1 mg of powder from a composite of between three and ten grains. In the case of YGML samples the minerals and glasses are, if not cogenetic, definitely erupted synchronously. With samples from the Bishop Tuff, however, it proved impossible to find pristine glass and coexisting large feldspar phenocrysts in individual pumice clasts and, as such, it cannot be proved that these samples are cogenetic. Although microprobe data do not record major element variations between different sized feldspar populations, the sampling for the isotopic work is undoubtedly biased to the largest feldspar grains. In order to assess if these feldspar populations have homogeneous Sr isotope ratios, multiple (bulk) and

individual feldspar grains were analysed as well as micro-drilled drilled core and rim composites. The majority of Sr isotope analyses were carried out at the University of Michigan following standard procedures (Halliday et al., 1989; Davies et al., 1994), the remainder at Amsterdam. Strontium isotope determinations at Michigan were performed on two V.G. Sector multicollector thermal ionization mass spectrometers. The average $^{87}\text{Sr}/^{86}\text{Sr}$ for NIST SRM 987 was 0.710258 ± 14 ($N > 100$) and the La Jolla Nd standard yielded $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511857 ± 6 ($N > 100$). The average $^{87}\text{Sr}/^{86}\text{Sr}$ for NIST SRM 987 was 0.710269 ± 16 ($N > 25$) and the $^{143}\text{Nd}/^{144}\text{Nd}$ of La Jolla was 0.511859 ± 9 ($N > 25$). Analyses at the Vrije Universiteit, Amsterdam, were performed on a Finnigan 261 with 9 fixed collectors. Strontium isotope ratios obtained at Amsterdam have been normalized to the Michigan value of 0.710258. The total blank for Sr is about 40 pg for the U-M analyses. The Sr isotope ratios of glasses were determined on relatively large sample sizes (35–55 mg) such that blank contribution to all glasses is below 0.1% and has been ignored. The blank in Amsterdam is consistently below 100 pg and any contribution can be ignored in all analyses except for the single feldspar grains from the Bishop Tuff that contain <10 ppm Sr. Blank corrections of between 0.4 and 1.5% have been applied in these cases. The analysed single feldspar grains are estimated to have contained ~10 ng of Nd. Neodymium blanks at Amsterdam during this work were ~30 pg. The blank Nd isotope composition is within 0.1% of the feldspar compositions, consequently blank corrections result in little change compared to the measured $^{143}\text{Nd}/^{144}\text{Nd}$. A conservative error estimate of 1% is used for isotope dilution Rb/Sr ratios in all age calculations.

3. RESULTS

3.1. Glass Rb-Sr Isotope Data

Rb/Sr ratios of rhyolite glasses from the young Glass Mountain lavas (YGML) range from 65.1 to 153.9 (Table 1), which means there is minimal overlap with the old Glass Mountain Lavas (OGML) (127.6 to 3637; Halliday et al., 1989; Davies et al., 1994). The Rb contents of the YGML glasses are lower than the OGML, 156.8–183.1 compared to 165–313 ppm, and Sr contents are all above 1.2 ppm compared to below 1 ppm for the OGML (Halliday et al., 1989; Davies et al., 1994). Despite the young age of the YGML (<1.2 Ma), the high Rb/Sr ratios result in a large amount of radiogenic ingrowth and consequently variable present-day $^{87}\text{Sr}/^{86}\text{Sr}$: 0.7087 to 0.7133. Throughout the paper, initial isotope ratios are calculated at the time of eruption (e.g., $^{87}\text{Sr}/^{86}\text{Sr}_e$) determined by K-Ar dating (Metz and Mahood, 1985). $^{87}\text{Sr}/^{86}\text{Sr}_e$ vary between 0.7054 and 0.7077. There is no simple temporal relationship between age of the lavas and $^{87}\text{Sr}/^{86}\text{Sr}_e$ (Table 1). The Rb-Sr data for glasses from the Bishop Tuff (Table 3) are within the range recorded in previous studies (Halliday et al., 1984; Christensen and DePaolo, 1993; Christensen and Halliday, 1996).

3.2. Mineral Rb-Sr Isotope Data

Mineral phases from YGML (YA and YG) have significant variations in present-day Sr isotope compositions (e.g., sanidine in YA 0.7063 to 0.7071; Table 2). The cores of sanidine and plagioclase have less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ than the bulk separates and individual grains (e.g., core 0.7062 compared to bulk 0.7064 for plagioclase in YA). The K-poor rims of both sanidine and plagioclase grains are significantly more radiogenic than the single grains and bulk separates (e.g., YA plag. rim 0.7072 compared to 0.7062 for core).

Table 1. Strontium and neodymium isotope data from young glasses

Sample	Age ² (Ma)	Rb ppm	Sr ppm	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr _e	¹⁴³ Nd/ ¹⁴⁴ Nd	ε _{Nd}
OUTER								
YO ¹ WR	1.06	182	1.20	439.1	0.71319 ± 2	0.70658 ± 9	0.51258 ± 1	−1.2 ± 0.2
YO G	1.06	183	1.19	445.4	0.713313 ± 14	0.70661 ± 8	0.51258 ± 1	−1.2 ± 0.2
YE ¹ WR	0.96	158	2.31	197.9	0.70924 ± 2	0.70654 ± 5	0.51260 ± 1	−0.8 ± 0.2
YE G	0.96	161	2.25	207.6	0.709418 ± 11	0.70659 ± 4		
YK ¹ WR	0.92	169	1.23	397.7	0.71244 ± 3	0.70724 ± 8	0.51259 ± 1	−1.0 ± 0.2
YU G	0.91	185	1.29	415.6	0.712800 ± 14	0.70743 ± 7		
YZ G	0.82	180	1.48	351.4	0.711782 ± 12	0.70769 ± 5		
YA ¹ WR	0.79	159	2.32	198.3	0.70940 ± 2	0.70718 ± 4	0.51259 ± 1	−1.0 ± 0.2
YA G	0.79	166	2.25	213.8	0.709491 ± 8	0.70709 ± 3		
YB G	^Λ	158	2.23	204.4	0.709345 ± 16	0.70673 ± 4		
YF G	^Λ	166	1.42	338.6	0.711523 ± 18	0.70720 ± 6		
Y3 G	^Λ	184	1.281	416.1	0.712816 ± 12	0.70750 ± 7	0.51258 ± 1	−1.1 ± 0.2
INNER								
Y5 G	1.2	161	2.25	206.7	0.708901 ± 12	0.70538 ± 5	0.51259 ± 1	−0.9 ± 0.2
Y6 G	1.06	165	1.28	374.3	0.711515 ± 12	0.70588 ± 8	0.51258 ± 1	−1.1 ± 0.2
YH G	0.94	163	1.48	318.4	0.710590 ± 18	0.70634 ± 6		
YG ¹ WR	0.9	162	2.49	188.3	0.70868 ± 2	0.70627 ± 4	0.51258 ± 1	−1.2 ± 0.2
YG G	0.9	165	2.28	209.5	0.708913 ± 16	0.70624 ± 4		
YT G	0.81	168	2.43	200.4	0.708791 ± 10	0.70649 ± 4		
YW G	^Λ	163	2.11	223.7	0.708211 ± 10	0.70635 ± 4		

¹ Rb-Sr data originally reported by Halliday et al. (1990).

² K-Ar ages from Metz and Mahood (1985); ^Λ assigned age of 0.9 Ma
W.R. = whole rock; G = glass.

Feldspar populations from the Bishop Tuff samples have very heterogeneous ⁸⁷Sr/⁸⁶Sr (0.706 to 0.715). Feldspar rims from the late Bishop Tuff have more radiogenic ⁸⁷Sr/⁸⁶Sr than the cores and bulk separates. In contrast, some feldspar rims from the early Bishop Tuff have Sr which is less radiogenic than that of the cores (0.706 compared to 0.709). The Sr isotope

compositions of bulk sanidine and bulk plagioclase composites and individual grains free of overgrowths from samples YA and YG are close to analytical error, which implies that the feldspars probably represent single populations (Table 2). Similarly, feldspars from the late Bishop Tuff have ⁸⁷Sr/⁸⁶Sr ratios that vary by only 0.000045, in contrast to the very

Table 2. Strontium and neodymium isotope data of minerals from young lavas

Sample	Rb ppm	Sr ppm	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr _e	Glass-mineral age; ka	¹⁴³ Nd/ ¹⁴⁴ Nd	ε _{Nd}
Sample YA								
Glass	166	2.25	213.8	0.709491 ± 8	0.70709 ± 3		0.51259 ± 1	−1.0 ± 0.2
Plag bulk	2.72	24.3	0.3237	0.706448 ± 11	0.70644 ± 1	1004 ± 16	0.51258 ± 1	−1.1 ± 0.2
Plag core ^a	2.69	29.9	0.2609	0.706224 ± 10	0.70622 ± 1	1078 ± 16		
Plag rim ^a	2.83	21.7	0.3787	0.707165 ± 10	0.70716 ± 1	768 ± 14		
Plag single	2.71	28.7	0.2724	0.706412 ± 22	0.70641 ± 2	1016 ± 20	0.51258 ± 1	−1.2 ± 0.2
Plag single	2.74	28.9	0.2745	0.706386 ± 19	0.70638 ± 2	1024 ± 19		
S. bulk	42.6	22.9	5.387	0.706801 ± 10	0.70674 ± 1	909 ± 16	0.51258 ± 1	−1.1 ± 0.2
S. core ^a	38.4	24.4	4.548	0.706425 ± 11	0.70637 ± 1	1059 ± 18		
S. rim ^a	4.63	18.4	0.7275	0.707215 ± 12	0.70721 ± 1	785 ± 14		
S. single	81.6	23.4	10.09	0.706715 ± 22	0.70660 ± 2	960 ± 21		
S. single	81.9	23.2	10.23	0.706724 ± 18	0.70661 ± 2	957 ± 20	0.51259 ± 3	−1.0 ± 0.6
Sample YG								
Glass	165	2.28	209.5	0.708913 ± 16	0.70624 ± 4		0.51258 ± 1	−1.2 ± 0.2
Plag bulk	4.04	39.4	0.2960	0.706021 ± 12	0.70602 ± 1	973 ± 19	0.51258 ± 1	−1.1 ± 0.2
Plag rim ^a	4.32	35.5	0.3526	0.706327 ± 11	0.70632 ± 1	871 ± 18		
Plag core ^a	3.86	43.3	0.2582	0.706012 ± 11	0.70601 ± 1	1010 ± 19		
Plag single	4.02	42.4	0.2741	0.706015 ± 16	0.70601 ± 2	975 ± 20		
Plag single	4.01	42.6	0.2724	0.706012 ± 18	0.70601 ± 2	976 ± 21	0.51258 ± 3	−1.2 ± 0.6
S. bulk	81.8	28.0	8.4615	0.706518 ± 11	0.70641 ± 1	874 ± 19	0.51258 ± 1	−1.1 ± 0.2
S. rim ^a	8.62	29.8	0.8360	0.706423 ± 11	0.70641 ± 1	840 ± 18		
S. core ^a	78.5	30.0	7.567	0.706085 ± 11	0.70599 ± 1	986 ± 20		
S. single	77.4	30.1	7.447	0.706145 ± 19	0.70605 ± 2	965 ± 23		
S. single	79.7	29.9	7.698	0.706149 ± 18	0.70605 ± 2	964 ± 22	0.51258 ± 3	−1.2 ± 0.6
Biotite	339	0.869	1130	0.719604 ± 18	0.70516 ± 16	818 ± 14		

^a composite

Table 3. Strontium and neodymium isotope data of minerals from the Bishop Tuff

Sample	Rb ppm	Sr ppm	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_e$	Glass-mineral age (ka)	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵ_{Nd}
LV-8 Early airfall Bishop Tuff								
Glass	194	2.00	279.5	0.709998 ± 12	0.70698 ± 4		0.51259 ± 1	-1.0 ± 0.2
S. bulk	120	23.4	14.85	0.706767 ± 13	0.70661 ± 1	860 ± 16		
S. core ^a	114	25.6	12.83	0.709514 ± 9	0.70938 ± 1	122 ± 7	0.51250 ± 1	-2.7 ± 0.2
S. rim ^a	15.9	45.3	1.017	0.706913 ± 12	0.70690 ± 1	777 ± 14	0.51251 ± 1	-2.5 ± 0.2
S. single	125	1.84	195.8	0.715260 ± 22	0.71314 ± 4	-1326 ± 5		
S. single	122	1.91	184.9	0.713001 ± 23	0.71100 ± 4	-756 ± 12		
S. single	109	23.5	13.35	0.706806 ± 16	0.70666 ± 2	804 ± 15		
S. single	91.7	1.99	133.5	0.711475 ± 24	0.71003 ± 3	-372 ± 5	0.51258 ± 4	-1.1 ± 0.8
S. single	114	14.0	23.47	0.706910 ± 16	0.70666 ± 2	778 ± 15	0.51248 ± 3	-3.1 ± 0.6
S. single	107	9.15	33.71	0.706950 ± 18	0.70659 ± 2	768 ± 15	0.51247 ± 3	-3.3 ± 0.6
S. single	115	2.21	150.7	0.708573 ± 20	0.70694 ± 4	359 ± 12		
Plag bulk	8.63	39.5	0.6317	0.706592 ± 9	0.70659 ± 1	858 ± 14		
Plag rim ^a	6.89	56.3	0.3542	0.706926 ± 12	0.70692 ± 1	774 ± 14	0.51252 ± 1	-2.3 ± 0.2
Plag core ^a	12.8	42.5	0.8687	0.707770 ± 10	0.70776 ± 1	561 ± 11	0.51251 ± 1	-2.5 ± 0.2
Plag single	10.9	41.3	0.7592	0.706236 ± 14	0.70623 ± 1	948 ± 16		
Plag single	13.1	26.5	1.437	0.706582 ± 13	0.70657 ± 1	861 ± 15	0.51258 ± 3	-1.1 ± 0.6
Plag single	13.8	21.5	1.863	0.706543 ± 14	0.70652 ± 1	871 ± 15	0.51249 ± 4	-2.9 ± 0.8
Plag single	14.6	4.47	9.485	0.707873 ± 24	0.70777 ± 3	541 ± 15		
Plag single	16.6	2.66	18.10	0.709740 ± 32	0.70954 ± 3	650 ± 12	0.51246 ± 4	-3.5 ± 0.8
LV-3 Late Bishop Tuff (Ig2N)								
Glass	128	30.1	12.27	0.706135 ± 11	0.70600 ± 1		0.51260 ± 1	-0.7 ± 0.2
Plag rim ^a	4.86	548	0.0256	0.705991 ± 10	0.70599 ± 1	886 ± 58		
Plag core ^a	4.05	573	0.0204	0.705952 ± 10	0.70595 ± 1	1110 ± 58		
Plag bulk ^b	3.32	297	0.0323	0.705978 ± 12	0.70598 ± 1	973 ± 69	0.51260 ± 1	-0.7 ± 0.2
Plag single	4.23	486	0.0252	0.705951 ± 16	0.70595 ± 2	1151 ± 92		
Plag single	4.67	557	0.0243	0.705971 ± 18	0.70597 ± 2	1047 ± 103	0.51258 ± 4	-1.1 ± 0.8
Plag single	4.48	468	0.0277	0.705986 ± 16	0.70599 ± 2	949 ± 92		
S. rim ^a	33.7	372	0.2620	0.705993 ± 10	0.70599 ± 1	892 ± 59		
S. core ^a	32.3	424	0.2205	0.705948 ± 10	0.70595 ± 1	1038 ± 59		
S. bulk ^a	42.4	383	0.3206	0.705969 ± 10	0.70597 ± 1	1038 ± 59	0.51259 ± 1	-1.0 ± 0.2
S. single	34.2	377	0.2625	0.705957 ± 18	0.70595 ± 2	1150 ± 106		
S. single	35.7	412	0.2509	0.705993 ± 18	0.70599 ± 2	938 ± 106	0.51258 ± 4	-1.1 ± 0.8

^a composite; ^b with inclusions

heterogeneous nature of minerals from the early Bishop Tuff (Table 3).

3.3. Neodymium Isotope Compositions

The Nd isotope ratios of glass and mineral phases from the YGML and the late Bishop Tuff are homogeneous and indistinguishable from previously reported values (Tables 1–3, Fig. 2, ϵ_{Nd} -1.7 to -0.9 ; Halliday et al., 1984, 1989). In contrast, phases from the early Bishop fall deposit are heterogeneous and the majority are significantly less radiogenic (ϵ_{Nd} -3.5 to -1.0) than the upper Bishop Tuff and the Younger Lavas (Fig. 2).

4. RB-SR ISOCHRON AGES

Glasses from YGML closest to the caldera margin (see Fig. 1) define a Rb-Sr isochron of 1.09 ± 0.03 Ma (MSWD of 3.25; Fig. 3). Glasses from lavas more distant from the caldera rim define a distinctly different Rb-Sr isochron age of 1.15 ± 0.01 Ma with a MSWD of 0.77 (Fig. 3). This age is within error of that determined by Halliday et al. (1989) for the same group of outer YGML (1.14 ± 0.08 Ma). Initial ratios for the two suites are distinct ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7057 \pm 1$ and 0.7060 ± 1) and the former is lower than the initial ratios of the two regional isochrons defined by the OGML (0.7063 ± 2 , 0.7062 ± 2 ;

Davies et al., 1994). The Nd isotope systematics of the two suites are identical but distinct from the OGML (Fig. 2) indicating a different mixture of source components. The YGML that define the regional isochrons have K-Ar ages that range from 1.06 to 0.79 Ma for the outer isochron and from 1.20 to 0.81 Ma for the inner isochron (Metz and Mahood, 1985). This implies magma chamber residence times of up to 360 kyr, indistinguishable from the maximum estimate of 360 kyr for the OGML (Davies et al., 1994). The similarity of these estimates may be coincidental but possibly represents an upper limit for survival times of magma batches in the LVHMS. The dividing line between inner and outer lavas trends NW-SE and is similar to the dividing line of the inner and outer lava groups of the OGML (Fig. 1). This implies that there is a significant crustal structure at depth that kept contemporaneous magma batches isolated from each other (Halliday et al., 1989; Davies et al., 1994).

The suggestion of magma storage times in excess of 100 ka has proved controversial (e.g., Sparks et al., 1991; Halliday, 1991; Mahood, 1991; Davies et al., 1994). The initial debate centered on the possibility that the regional isochrons and their relatively small errors could record the time and duration of magma production in the lower crust (Sparks et al., 1991). Melt generation was envisaged as a consequence of basalt intrusion following the model of Huppert and Sparks (1988). Although

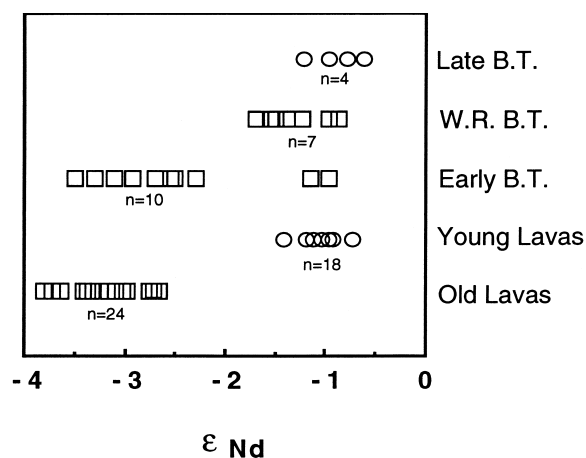


Fig. 2. Diagram summarizing the Nd isotope composition of lavas and minerals from Long Valley rhyolitic magmas (data sources: Halliday et al., 1984, 1989; Davies et al., 1994). Note the distinct Nd isotope compositional gap between the young and old Glass Mountain lavas. The earliest Bishop Tuff contains feldspars with Nd isotope compositions similar to both old and young Glass Mountain Lavas demonstrating a mixed provenance for minerals within the earliest Bishop Tuff.

such a model is a highly plausible method for producing granitic melts, the extreme trace element contents of the Long Valley magmatic system, notably the high Rb/Sr ratios, require extensive feldspar fractionation after initial melt generation (e.g., Halliday et al., 1991). This observation, coupled with possible crustal interaction during magma transport from the lower crust, appears to rule out the isochrons being a consequence of lower melting crustal processes (Halliday, 1991).

From the above data we can add little in the way of new insights to the problem of how magmas may be stored for extended periods other than to emphasize that the high-silica magmas have such low Sr contents that any Rb/Sr isochrons would be easily disrupted by (1) crystallization and separation of any Sr bearing phase (feldspar, biotite, etc.), (2) addition of new magma, (3) assimilation of crustal country rocks, (4) assimilation of cumulate material, and (5) partial assimilation of a frozen rind surrounding the magma body. Therefore, the preservation of these isochrons provides strong evidence against the importance of these processes. In addition, magma mixing must be limited to preserve the large range of Rb/Sr ratios.

Recently Knesel and Davidson (1997) have argued that the partial assimilation of magma chamber wall rocks could be responsible for the pre-eruptive ages of the Glass Mountain lavas. Citing examples of melts that are in chemical and isotopic disequilibrium with their host (e.g., Tommasini and Davies, 1997), they argue that an AFC process, involving the preferential incorporation of melts derived from dehydration of biotite, may explain the pre-eruptive ages of the Glass Mountain lavas. Knesel and Davidson (1997), however, appear to have ignored the fundamental observation that the four regional isochrons defined by Glass Mountain lavas are for rocks that were erupted over periods of at least 300 ky and that the regional isochron ages are close to the eruption ages of the oldest lavas that define each isochron; i.e., the isochrons do not

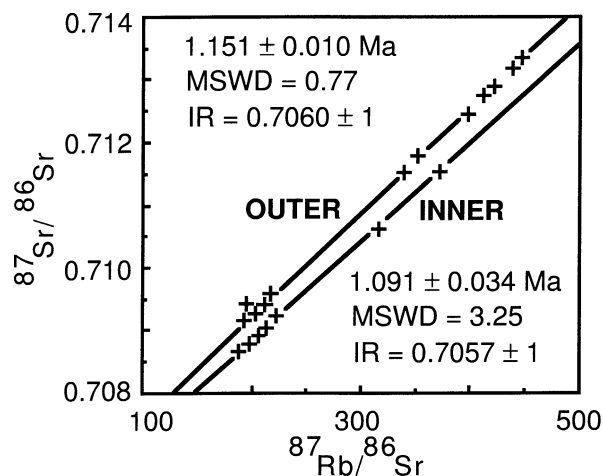


Fig. 3. Rb-Sr isotope diagrams for glasses and whole rocks from young Glass Mountain Lavas. Nine outer lavas define an isochron of 1.151 ± 0.010 Ma with an initial ratio of 0.7060 ± 1 . Six inner lavas define an isochron of 1.091 ± 0.034 Ma with a distinctly different initial ratio of 0.7057 ± 1 .

define pre-eruptive ages for all the lavas. In addition, there is no temporal control to the Rb/Sr or $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the lavas as might be predicted from an AFC process. The magma chambers were clearly active for protracted periods and did not undergo significant chemical changes after eruption began, i.e., the isochrons were not disrupted over periods of at least 300 ky. Consequently, it must be concluded that although an ad hoc contamination process could explain pre-eruptive ages of individual eruptions or plutons, it is an untenable explanation for the precise isochrons defined by Glass Mountain lavas and the inferred pre-eruptive ages.

Recently several other studies have presented evidence for extended magma storage times. Post-caldera rhyolites at Long Valley have both Rb-Sr and U-Th systematics that imply magma storage times in excess of 100 ka (Heumann and Davies, 1997; Reid et al., 1997). Further support for extended magma storage times comes from other evolved magmatic systems (Mount St. Helens: Volpe and Hammond, 1991; Naivasha, Kenya, Heumann et al., 1995, and Black et al., 1997; Baitoushan, China, Dunlap and Gill, 1997). These data provide compelling evidence that magmas are stored in the crust for extended periods without being effected by igneous processes that fractionate parent-daughter systems (Rb-Sr and U-Th) with very different geochemical properties.

5. MINERAL ISOTOPIC SYSTEMATICS

In the following sections we report Rb-Sr glass-mineral ages (hereafter referred to as mineral ages or feldspar ages) from the YGML and Bishop Tuff and then use the Nd isotope systematics of the minerals to assess if the mineral ages are possibly valid. In a later section we undertake a detailed analysis of all chemical, isotopic and petrologic data to establish if there is geological significance to these ages and assess the petroge- netic implications of these data.

5.1. Young Glass Mountain Lavas: YA and YG

Sample YG has an eruption age of 0.90 ± 0.06 Ma (Metz and Mahood, 1985) and lies on the inner regional Rb-Sr isochron (1.091 ± 0.034 Ma). YA has an eruption age of 0.79 ± 0.04 Ma (Metz and Mahood, 1985) and lies on the outer regional Rb-Sr isochron (1.151 ± 0.010 Ma). The Nd isotope data for mineral and glass separates from YA and YG, presented in Table 2, are within analytical error (Fig. 2). This implies that the feldspars and host glasses could be cogenetic. It is therefore valid to report Rb-Sr ages of the feldspars assuming a cogenetic origin with the glass and hence the same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Rb-Sr feldspar ages range from 1.010 ± 0.019 to 0.840 ± 0.018 Ma in sample YG and from 1.078 ± 0.016 to 0.768 ± 0.014 Ma in sample YA (Fig. 5; Table 2). If one simply ignores the possible consequences of diffusive exchange (see later discussion), these data imply that feldspars and their host glass (magma) were in contact for up to 300 kyr.

Mineral ages determined on the translucent plagioclase overgrowths from YA and YG are significantly younger than for the individual and bulk grains (Fig. 5; Table 2). The youngest ages from each sample are within error of the eruption age of the host lava, supporting the validity of the K-Ar results (Metz and Mahood, 1985). In the case of sample YA, one of the rim ages (768 and 785 ± 14 ka) is within error of the eruption age of the Bishop Tuff (Fig. 5a; 759 ± 3 ka, Pringle et al., 1992; 761 ± 1 ka, van den Bogaard and Schirnack, 1995).

The mineral ages of cores and single grains are significantly older than the rims and older than the eruption age of the host lavas (Fig. 5). Plagioclase grains are all older than 1.0 Ma whereas the sanidine ages scatter about 1.0 Ma (Fig. 5; Table 2). These ages are close to that of the regional isochron and imply that the majority of feldspar crystallization occurred rapidly, compared to the inferred magma residence times, probably associated with, or immediately following, the initial differentiation event that produced the outer regional isochron (Fig. 5). Mineral ages from sample YG are generally younger than from YA by ~ 50 kyr but again cluster around 1.0 Ma and approach the age of the inner regional isochron (Fig. 5b; Table 2).

5.2. Bishop Tuff

Feldspars from the late Bishop Tuff are in Nd isotope equilibrium with each other and their host; $\epsilon_{\text{Nd}} -0.7$ to -1.1 (Fig. 2). In contrast, feldspars from the early Bishop Tuff are heterogeneous, $\epsilon_{\text{Nd}} -1.1$ to -3.5 (Fig. 2). It is therefore apparent that, although geologically significant ages may be obtained from the late Bishop Tuff, great caution must be taken in the interpretation of the Rb-Sr isotope systematics of the early Bishop Tuff (cf. Halliday et al., 1984; Christensen and DePaolo, 1993; Christensen and Halliday, 1996). The plagioclase and sanidine mineral ages from the late Bishop Tuff share similarities with those obtained from the YGML in that core ages are older than 1.0 Ma and rim ages approach the eruption age of the Bishop Tuff (Fig. 5; Table 3). The notable difference is that the ages for a single phase are significantly more scattered than from the YGML (e.g., sanidine core 1.04 Ma and single sanidine grains yield ages as young as 0.89 Ma; Table 3, Fig. 5c).

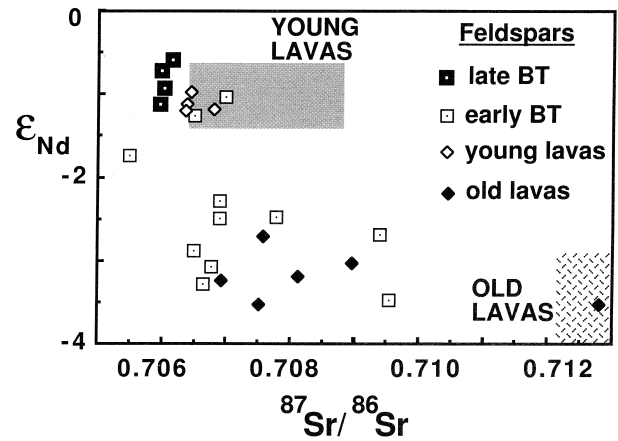


Fig. 4. Sr-Nd isotope diagram for minerals and glasses taken from the Bishop Tuff and Glass Mountain Lavas plotted at the time of Bishop Tuff eruption (760 ka). Note that feldspars from the early Bishop Tuff have isotopic compositions similar to both younger and older Glass Mountain Lavas demonstrating a mixed provenance (Davies et al., 1994).

Feldspar ages from the early Bishop Tuff range from 1.22 to -1.33 Ma and record significant scatter when initial ratios are plotted on a Sr-Nd isotope diagram (Fig. 4). The negative ages are a clear indication that some phases have not reached Sr isotope equilibration with their current host glass. Mineral ages of the feldspar rims (777 and 774 ± 14 ka) are close to the eruption age of the Bishop Tuff and may imply that some feldspars growth probably occurred in the Bishop Tuff magma chamber close to the time of eruption. In addition to the Sr isotope heterogeneity of the minerals, Sr contents vary by a factor of >20 (plagioclase Sr contents between 2.7 and 56.3 ppm; Table 3). Feldspars record a general positive correlation between Sr contents and Nd isotope ratios, which demonstrates that the early Bishop Tuff contains material that did not crystallize from the host magma (Figs. 2 and 4; Table 3). The Nd and Sr isotope systematics of both sanidine and plagioclase with the lowest Sr contents are comparable to minerals from the OGML (Fig. 4; Davies et al., 1994) implying that these phases may have originated from the magmas that formed the OGML. Further evidence for such an origin is provided by the K-Ar isotope systematics of melt inclusions in quartz from Bishop airfall and an early Bishop ignimbrite (Ig1E). Quartz grains formed close to 2 Ma and one population defines an $^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$ isochron with an age of 1.93 ± 0.12 Ma (van den Bogaard and Schirnack, 1995). This age is within error of the two regional Rb-Sr isochrons defined by the older Glass Mountain lavas (Halliday et al., 1989; Davies et al., 1994). Rb-Sr systematics of several melt-inclusion bearing quartz grains taken from Bishop airfall also have been interpreted to indicate derivation from older Glass Mountain-like magmas (Christensen and Halliday, 1996).

6. INTERPRETATION OF MINERAL DATA

6.1. Age Significance

From the above discussion it appears that both early and late erupted sections of the Bishop Tuff contain earlier formed

mineral phases that were incorporated into the Bishop Tuff magma. The pre-eruptive ages of feldspars from the YGML could be interpreted in the same way. There are three physical processes that could be responsible: (1) incorporation from country rock during the eruption process, (2) incorporation through the disruption of a crystal-rich and/or solid margin to the magma body prior to or during eruption (e.g., Mahood, 1991), or (3) mineral grains that crystallized from the magmas that formed the young and old Glass Mountain lavas and resided in the magma chamber for $>10^5$ yr (Halliday et al., 1989). Below we will use the available isotopic and petrologic data to distinguish between these possibilities and use “phenocrysts” as a nongeneric term in the discussion.

The low Sr contents and relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ of the feldspar “phenocrysts” establishes that they cannot have been derived from the local country rock which is characterized by higher Sr contents and generally more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (see Davies et al., 1994, for greater discussion). Wilson and Hildreth (1997) have demonstrated that the lithic fraction of some late ignimbrite flows (Ig2 N and E) comprises up to 80% Glass Mountain rhyolite. Consequently an eruption related xenocrystic origin for the feldspars appears a possibility. However, all the isotopic data for the Bishop Tuff “phenocrysts” presented above and previously reported by other workers, were obtained on minerals separated from pumice clasts. In addition, most of the pre-eruption mineral ages obtained by Sr and Ar techniques are from the Bishop airfall, which does not contain significant lithics of Glass Mountain rhyolite (Wilson and Hildreth, 1997). Further evidence against an eruption related xenocrystic origin for the feldspars comes from Ar-Ar dating of the Bishop Tuff. Incorporation of feldspar into the relatively cool Bishop Tuff magma during eruption would not allow a total resetting of the K-Ar systematics (e.g., Lo Bollo et al., 1987; Feldstein et al., 1994). The consistent Ar-Ar ages obtained on sanidine grains (e.g., van den Bogaard and Schirnack, 1995) strongly argues against addition of the feldspars to the Bishop Tuff magma immediately prior to eruption.

Consideration of Sr diffusion within feldspars potentially provides a method for distinguishing between an origin of the feldspar as phenocrysts that have extended residence times within the host magma in contrast to derivation as xenocrysts from a disrupted crystallized rind. In a previous study of the OGML, Davies et al. (1994) presented a detailed discussion of the predicted extent of Sr isotope re-equilibration between feldspars and their host magma due to diffusive exchange, following the mathematical solutions of Crank (1975). Given the low magma temperatures of $\sim 700^\circ\text{C}$ for the YGML (Metz and Mahood, 1991), low Sr diffusion coefficients (for recent reviews see Giletti and Casserly, 1994; Cherniack, 1996), and that only large feldspar grains were analysed in this study (0.5 to 0.75 cm), diffusion calculations demonstrate that only the rims of grains would suffer significant Sr isotope exchange with a host magma over a timescale of $1\text{--}3 \times 10^5$ yr. Rim ages were obtained on the outer $\sim 100\ \mu\text{m}$ of grains. Although mineral rims will have undergone diffusional exchange with the host magmas on a $1\text{--}3 \times 10^5$ yr timescale, the magmas will be changing Sr isotope composition with time due to their relatively high Rb/Sr ratios. Consequently diffusion calculations demonstrate that the outermost $100\ \mu\text{m}$ of a grain will not reach the isotopic composition of the host magma by diffusion

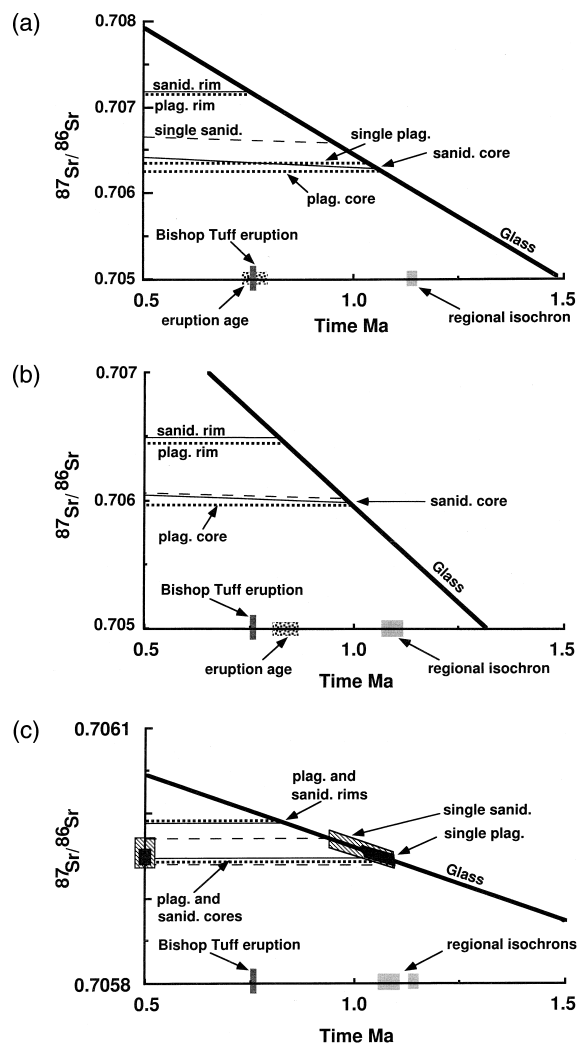


Fig. 5. Strontium isotope evolution diagram for young Glass Mountain Lavas and Bishop Tuff. Thick solid lines for glass; thin solid lines for sanidine rims and cores; dashed lines single sanidine grains; dotted lines plagioclase grains. (a) Lava YA. Sanidine and plagioclase rim ages are within error of the eruption age of the Bishop Tuff and lava. Core ages approach that of the regional Rb-Sr isochron. (b) Lava YG. Sanidine and plagioclase rim ages are within error of the eruption age of the lava but significantly older than the Bishop Tuff. Core ages approach that of the regional Rb-Sr isochron. (c) Late erupted Bishop Tuff. Sanidine and plagioclase rim ages are significantly older than the eruption age of the Bishop Tuff. Core ages approach that of the regional Rb-Sr isochrons and mineral rim ages the time of Bishop Tuff eruption.

alone. The fact that the rim ages from the early Bishop Tuff and lavas YA and YG are equal, or very close, to the eruption age of their host rock (Fig. 5), implies that there was some mineral crystallization close to the time of eruption. The different textures of the feldspar overgrowths suggest rapid crystallization under fluid rich conditions (Davies et al., 1994) which we interpret as a consequence of eruption related processes. The isotope data prove, for both YGML and the Bishop Tuff, that feldspar grains were resident in the magma chamber prior to eruption for a sufficiently long period to allow rim growth.

Diffusion calculations further imply that even if feldspar “phenocrysts” had been in the YGML magmas since formation

of the regional isochrons (<360 kyr) the cores of both sanidine and plagioclase grains would be unaffected by isotopic equilibration with the host magma. Hence the calculated mineral ages of feldspar cores (Fig. 5; Table 2) are expected to be of geological significance. Notably, the ages are close to those defined by the regional isochrons, which suggests formation associated with the differentiation event that caused the major Rb/Sr fractionation (Fig. 5) and formation up to 290 kyr prior to eruption of the host lava. The single and bulk sanidine ages from YGML are, on average, lower than the single and bulk plagioclase ages. This could be interpreted as evidence of younger crystallization or that the sanidine has undergone greater isotopic equilibration with the host magma. The calculated sanidine diffusion coefficients (Or_{61}) are, however, more than a factor of 10 slower than for albitic plagioclase (An_{15}) (Giletti and Casserly, 1994; Cherniak, 1996), apparently ruling out diffusion as the cause of the different mineral ages. Davies et al. (1994) argued on the basis of mutual feldspar inclusion relationships that similar age differences in the OGML were a consequence of earlier plagioclase crystallization.

Mineral ages calculated from a single lava use a common glass composition. A partial derivative analysis of the error in the age difference between minerals establishes that the contribution of the analytical error of the glass composition is minor (Davies et al., 1994) and therefore the differences in ages between phases are significant (Table 2; e.g., for sample YA $t_{\text{plag. core}} - t_{\text{sanid. core}}$ is 19 ± 5 kyr). Taken together, the single grain and core mineral ages are relatively homogeneous suggesting that the sampled minerals crystallized within ~50 kyr in both sample YA and YG. This further implies that the crystallization histories of the feldspars were episodic with a long period of negligible mineral growth between ~1.0 Ma and eruption at ~0.9 and ~0.79 Ma, respectively.

In the late Bishop Tuff mineral ages from plagioclase and sanidine cores are identical within error and are within error of the regional isochrons defined by the YGML (Fig. 5c). This similarity strongly implies formation in the same differentiation events that produced the YGML and storage of up to 390 kyr prior to eruption. If the feldspars resided in the magma for this entire period, the extent of Sr equilibration with the host magma would be greater than in the YGML, due to the hotter estimated temperatures for the late formed Bishop Tuff, but the effect on core compositions would still be negligible. The distribution of the feldspar mineral ages (between 1.15 and 0.94 Ma) could therefore be explained by crystallization from either the YGML or the Bishop Tuff because the initial ratios of the two systems are similar and the Rb/Sr ratios of the YGML are not extremely high. A significant observation is that the ages for a single phase from the Bishop Tuff are more variable than a single phase from the YGML (Fig. 5; Tables 2 and 3). However, the calculated degree of Sr diffusion expected in 400 kyr (1.15 Ma to 0.76) does not appear large enough to explain this observed age range, despite hotter conditions and faster diffusion. Therefore, although the absolute mineral ages of the Bishop Tuff feldspars may not be correct, the large variation in Sr isotope systematics implies mineral formation over extended time periods (hundreds of kyr). An important proviso to this conclusion and any conclusion regarding the crystallization ages of “phenocrysts” from the YGML and the early Bishop Tuff is that sampling of the minerals has not been representa-

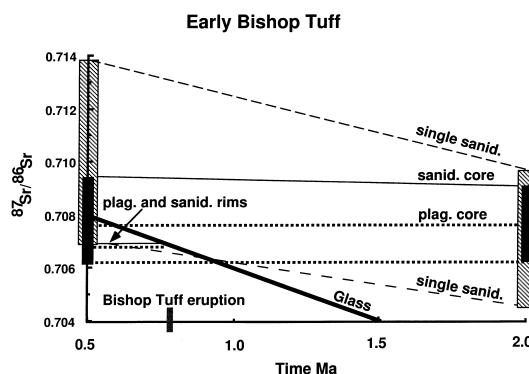


Fig. 6. Strontium isotope evolution diagram for early Bishop Tuff. Motif as in Fig. 5. Shaded area encompasses plagioclases and hashed areas sanidines. Sanidine and plagioclase rim ages are within error of the eruption age of the Bishop Tuff. Some sanidine and plagioclase grains have never been in isotopic equilibrium with the host glass and yield ages significantly younger than the eruption age of the Bishop Tuff.

tive. Material that was clearly xenocrystic in origin on the basis of morphology was rejected and only the largest grains have been hand-picked. The similarity in Rb-Sr isotope systematics for bulk, single and composite core samples does, however, suggest that the samples are representative of the majority of the larger feldspars in the rocks.

The extreme heterogeneity of feldspar Sr isotope ratios from the early Bishop Tuff implies that they have a complex petrogenesis. The combined Sr-Nd isotope systematics (Fig. 4) suggest that there are two distinct groups. The first group has relatively high Sr contents and ϵ_{Nd} values similar to the YGML (Fig. 4). The second feldspar group has lower Sr contents and lower ϵ_{Nd} values more comparable to the OGML (Fig. 4) (note that the two groups could not be distinguished petrographically and there appear to be no characteristic major element differences). Some of the feldspars of the first group yield Sr mineral ages between the age of Bishop Tuff eruption and the regional isochron ages defined by the YGML (Fig. 6). In contrast, feldspars from the second group yield mineral ages that are geologically unreasonable ranging from close to the eruption age of the Bishop Tuff to negative ages (–1.3 Ma; see Table 3 and Fig. 6). Significantly, both sanidine and plagioclase cores yield mineral ages that are younger than the eruption age of the Bishop Tuff (Table 3; Fig. 6). These data clearly establish that the entire feldspar population cannot be considered cogenetic. However, the similarity of the second feldspar group to the OGML could imply derivation from this magma source and consequently magma chamber residence times of up to ~1.3 Myr, as proposed by van den Bogaard and Schirnack (1995) and Christensen and Halliday (1996) (i.e., since formation of the oldest Long Valley silicic magmas at ca. 2.0 Ma; Metz and Mahood, 1985). The OGML record two regional Sr isochrons with indistinguishable initial ratios (0.7063 ± 2 , Davies et al., 1994). One has to be cautious in interpreting any Sr isotope model ages for early Bishop Tuff minerals calculated relative to this initial ratio. The available mineral ages from the OGML establish that initial mineral growth occurred for up to 80 kyr (Davies et al., 1994). In this period of time, due to the extreme Rb/Sr ratios of the OGML, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the magmas

could have increased from 0.7063 up to 0.7188 (Fig. 4). In addition, Sr diffusion calculations demonstrate that sanidine grains studied from the Bishop Tuff would exchange ~25% of their total Sr with the host magma in 1.3 Ma. Plagioclases would exchange closer to 40% of their Sr in the same period of time. Cores of grains would be little effected by Sr diffusional exchange but bulk sampling will yield disturbed Sr isotope systematics. Above 700°C Rb diffusion in sanidine is greater than for Sr (Giletti, 1991). As a consequence of at least one population of the feldspars being derived from magmas comparable to the OGML, i.e., higher Rb contents, the Rb/Sr ratios of these feldspars will be significantly altered by diffusional processes if the “phenocrysts” have resided in a magma for over 1 Myr. From the discussion above it is clear that any feldspar ages calculated using an assumed initial ratio are unlikely to be geologically reasonable. Therefore, the combined Sr-Nd isotope data from the cores of the feldspars can be used to make comparisons with possible source rocks but cannot provide absolute age information.

Christensen and Halliday (1996) presented Nd isotope data on composite quartz samples from the airfall section of the Bishop Tuff (three samples yield ϵ_{Nd} of -1). They argued that these quartz composites were derived from magmas contemporaneous to the OGML and hence that there were at least two isotopically distinct magma sources in the Long Valley system circa 2.0 Ma. The data presented above clearly demonstrate that the minerals in the airfall Bishop Tuff are from multiple sources comparable to the YGML and OGML, so it is difficult to interpret the significance of the quartz composite samples. In addition, two of the quartz composites and quartz-feldspar pairs from the third sample presented by Christensen and Halliday (1996) yield Rb-Sr model ages of ~1.2 Ma, i.e., within error of the regional isochrons of the YGML. Consequently, a simpler explanation of the Nd isotope data presented by Christensen and Halliday (1996) is that the quartz samples were predominantly derived from magmas comparable to the YGML. Further detailed work, however, is required to resolve this question.

Unfortunately we have to conclude that despite the detailed sampling undertaken in this study we are still unable to use the isotope data to unambiguously distinguish between the magma rind and long magma residence models for the origin of feldspar “phenocrysts” in the YGML and Bishop Tuff. This is due to feldspars having too short a residence in the YGML and late Bishop Tuff to allow Sr diffusion to produce a characteristic isotopic signature. The mixed feldspar populations in the early Bishop Tuff means that we cannot compare the average ages of plagioclase and sanidine to see if the age distribution is controlled by diffusion. Systematic sampling of the different populations is required, but at present we know of no nondestructive analytical method that will enable different feldspar populations to be distinguished prior to isotopic analyses. The ideal method to distinguish between the two potential models requires detailed isotopic profiles across individual grains. Due to the low Sr contents of the feldspars this was beyond our analytical capabilities. An additional aspect of studies that consider elemental diffusion is that the experimental diffusion coefficients are determined on gem quality minerals. Although the minerals in the LVHMS are well crystallized, it is unclear to what extent minor structural defects and melt and fluid inclusions will have on actual diffusion coefficients.

In order to distinguish between the magma rind or extended residence models for the genesis of the feldspars we have to combine our data with existing evidence. The first significant observation is that all phases studied are euhedral and occur as single unbroken grains. Disruption of a solid rock by the forceful eruptions associated with the formation of the Bishop Tuff would be expected to produce fractured minerals and mineral aggregates. Such relationships have been observed in products of the Fish Canyon Tuff where cracked and fragmented feldspar grains have granophyric overgrowths (Lipman et al., 1997) and in ash-flow tuffs throughout the Great Basin of the western USA (Best and Christiansen, 1997). Secondly, Hervig and Dunbar (1992) present trace element profiles across sanidine grains from the Bishop Tuff. Sanidines from the late Bishop Tuff ignimbrites (Ig2 E, N, NW) have complex trace element distributions. The cores of the grains have relatively constant Sr and Ba content (inner 50% by radius; Dunbar and Hervig, 1992). The subsequent ~30% of the grains records close to a 100% increase in Sr content. These profiles are consistent with the diffusion calculations outlined above and suggest that the mineral grains had residence times >100 kyr in a magma with greater Sr contents. The outermost ~100–150 μm of the grains have even higher Sr contents and Ba increases by over an order of magnitude. This latter observation is the reason that Hervig and Dunbar (1992) argued for the addition of a second magma into the base of the Bishop Tuff magma chamber shortly prior to eruption. This interpretation appears valid and is consistent with the rim ages of the feldspar being close to the time of Bishop Tuff eruption, which in turn indicates isotopic equilibration between the host glass and the mineral rims. The rim data do not, however, obscure the evidence for a significant trace element profile which we ascribe to element diffusion over an extended period of magma residence in the relatively deeper, hotter, and Sr-rich section of the Bishop Tuff magma chamber.

On the available evidence we therefore prefer a model in which the feldspar “phenocryst” population of the YGML represent true phenocrysts that have been resident in the magma chamber for up to 290 kyr. The feldspar “phenocrysts” of the late Bishop Tuff appear to have formed from the same source as “phenocrysts” in the YGML. Hence this feldspar population has always resided in the same magma chamber. The host magma was modified immediately prior to eruption, establishing that true Sr isotope mineral-glass ages cannot be determined on the feldspar population, with the exception of mineral rims. The combined Sr-Nd data do, however, place important temporal and petrogenetic constraints on the origin of the feldspar xenocrysts. Some feldspar crystals in the early Bishop Tuff appear to have formed from the same source as the OGML and possibly imply storage in the LVHMS for up to 1.3 Myr.

6.2. Mineral Growth Rates

From the proceeding discussion we conclude that the Rb-Sr mineral ages of the cores and rims of feldspars from the YGML provide information about the time of mineral growth. The age information can be used to estimate mineral growth rates. The feldspar grains used in this study were between 0.75 and 0.5 cm in diameter. The best age constraints are provided by sample

YA which lies on the inner regional isochron (1.151 ± 0.010 Ma). The youngest plagioclase grain yields an age of 1.016 ± 0.016 Ma. By simply assuming continuous growth for the largest grains, the age difference implies linear growth rate of $\sim 9 \pm 2 \times 10^{-14}$ cm/s, comparable to estimates made from the OGML (Davies et al., 1994). Clearly, assumption of continuous growth is speculative and can only be justified by lack of any apparent major element zonation in the feldspars, with the notable exception of the translucent rims. Mineral growth rates have been estimated for a number of phases from natural systems that range from basaltic to carbonatitic in composition (e.g., Cashman, 1991). Values of between 2×10^{-7} and 4×10^{-11} cm/s are obtained from measurements in lava lakes (Cashman, 1991). However, these measurements are made under conditions of rapid cooling (ca. 1°C/yr). At Glass Mountain, cooling rates must have been significantly lower for the magmas to remain molten over $>10^5$ yr. The distinction in mineral growth rates between basaltic and silicic systems are probably not only a consequence of different magma cooling rates but also a reflection of the differences in melt structure with high-silica magmas being highly polymerized.

7. TEMPORAL EVOLUTION OF LONG VALLEY MAGMA CHAMBER

The conclusions reached above allow constraints to be placed on the temporal evolution of the Bishop Tuff magma chamber. At ca. 2.0 Ma two magma batches were formed by the rapid differentiation of magmas from sources with similar Sr and Nd isotope systematics (Fig. 7a,b). The two magmas coexisted and were episodically tapped until ~ 1.2 Ma when the upper part of the magma chamber underwent a major mixing event with the addition of fresh, less evolved magma, resulting in more radiogenic Nd isotope ratios for all subsequent high-silica lavas. Shortly after this time, two separate magma batches of high-silica magma were again formed in rapid differentiation events (Fig. 7c). The two magmas coexisted and were episodically tapped until the eruption of the Bishop Tuff at 0.76 Ma. This eruption, which was associated with some feldspar growth, appears triggered by the addition of a less differentiated magma that contained greater Sr and Ba (Fig. 7d; Hervig and Dunbar, 1992). A more detailed study is required of the chemical and isotopic variations of minerals and host glass throughout the eruptive sequence to determine the extent of magma mixing and the influence of this new magma in producing the chemically zoned magma chamber that was subsequently sampled during eruption of the Bishop Tuff. The Bishop Tuff contains minerals that appear to have been derived from both pre-1.2 and post-1.2 Ma magmas. Minerals crystallized from the oldest magmas were not uniformly redistributed throughout the magma chamber. They have not, so far, been recorded from the YGML or the hotter (later) portions of the Bishop Tuff, implying that they remained isolated in the upper portions of the magma chamber or were resorbed at greater depth.

Provided that the long magma residence times for the feldspar "phenocrysts" are accepted, then the possible explanation for the heterogeneity of mineral ages from the Bishop Tuff comes from a consideration of the probable dynamics of the Bishop Tuff magma chamber. Compared with the Bishop Tuff,

the older and younger Glass Mountain Lavas are more chemically evolved and equilibrated at similar or lower temperatures. This suggests that the Bishop Tuff sampled the magma system to greater depth. The regional Sr isochrons recorded by both the YGML and OGML only place constraints on the physical processes operating in the upper parts of the magma system (i.e., no disruption of the isochrons by mixing or significant mineral crystallization). The less chemically evolved and hotter magmas at greater depth in the magma system may have undergone greater degrees of mixing and several periods of crystallization. Periodic replenishment of the LVHSMS by basaltic material at depth is required to compensate for cooling (Halliday, 1991). The large size of the magma chamber (hundreds of km^3 ; Hildreth, 1979) would lead to any large temperature variations at depth being dampened at higher levels. Consequently crystallization/resorption should be more common at greater depth, where temperatures are expected to be more variable, than at the top of the magma chamber, tapped by the YGML and OGML.

The regional control to magma composition has been explained as a consequence of magma stratification, or by having totally separate magma bodies, or subparallel cupolas (Halliday et al., 1989). The presence of a physical structure at depth to separate co-existing magma batches clearly explains the similar regional control to the distribution of younger and older Glass Mountain lavas.

8. MAGMA PRODUCTION RATES

The preservation of four regional Rb-Sr isochrons in the Glass Mountain lavas establishes that the chemical fractionation process(es) that produced these extreme magma compositions occurred rapidly. We cannot define exactly the nature of this differentiation process other than to say:

- 1) Neodymium isotopes require that a major component of the magma body was recently derived from the mantle (Halliday et al., 1989). Hence, partial melting in the mantle or of recently formed lower crust is probably involved.
- 2) The high Rb/Sr ratios and low Sr contents of the Glass Mountain Lavas and early Bishop Tuff require that their parental magmas have undergone large amounts of fractionation of an assemblage with a bulk Sr D of >2 (i.e., dominated by sanidine and plagioclase, Halliday et al., 1991). The phenocryst populations of Glass Mountain lavas have bulk Sr partition coefficients well in excess of 2, but the observed population is sparse and alone cannot be responsible for magma differentiation. Large amounts of feldspar rich "cumulates" are required at depth.

The actual volume of the erupted lavas at Glass Mountain is unknown due to disruption by caldera formation. The YGML today form $>25 \text{ km}^3$ of which $\sim 15 \text{ km}^3$ are from lavas that lie on the outer regional isochron. This provides a lower limit on the size of the magma chambers. The outer regional isochron has a precision of $\pm 10,000$ yr which implies that the precursor to the silicic magma differentiated rapidly and produced high-silica rhyolite at a rate of at least $0.75 \times 10^{-3} \text{ km}^3/\text{yr}$. This rate is identical to estimates made for the OGML following the same lines of reasoning ($0.8 \times 10^{-3} \text{ km}^3/\text{yr}$; Davies et al.,

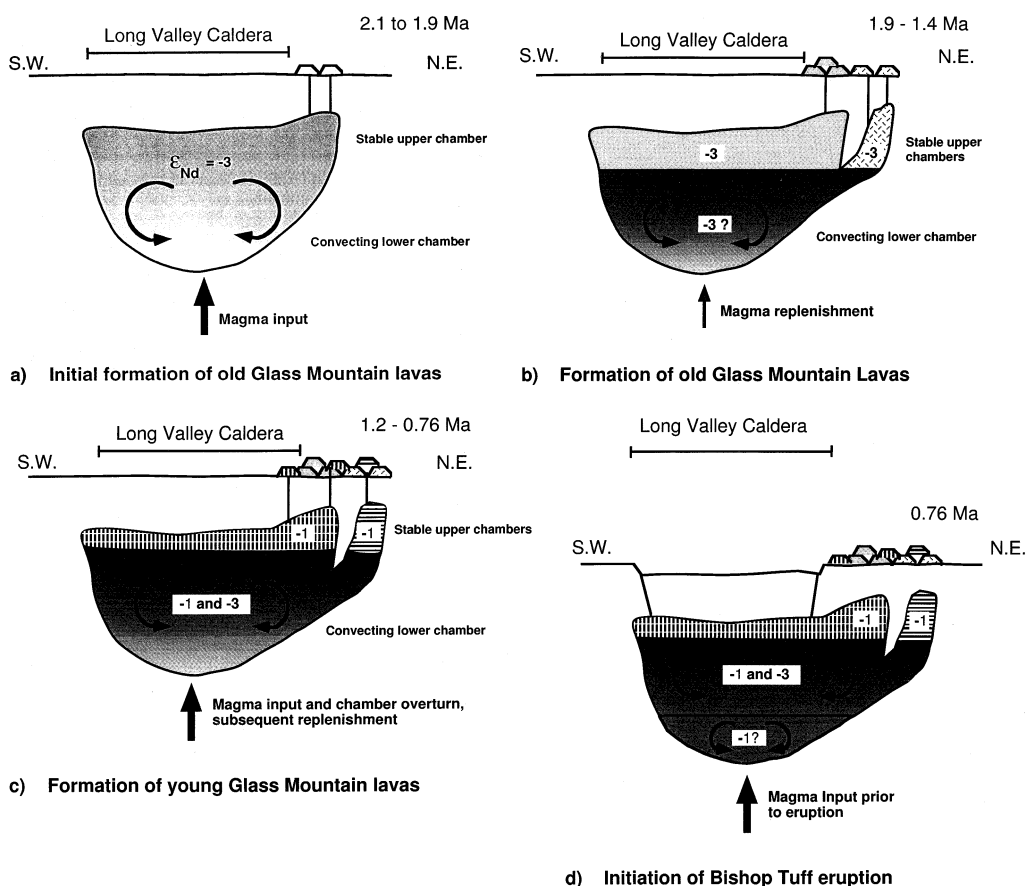


Fig. 7. Schematic SW-NE sections depicting the probable evolution of the Long Valley magma system. (a) Emplacement through dyke system of large volumes of high-silica magma (up to 500 km³) and rapid subsequent stratification to form a roof zone of highly differentiated magma (>15 km³). Eruption of lava domes begins at ~2.1 Ma (Metz and Mahood, 1985). (b) Circa 1.9 Ma, a second stratified roof zone is formed (>5 km³). The Sr-Nd-Pb isotope systematics are indistinguishable from the first magma batch so it is impossible to establish if the second magma batch was formed due to the addition of a chemically similar magma or that changes in the geometry of the magma chamber allowed separation of a second capping magma. Lava domes are erupted concurrently from the two magma systems over 0.5 My demonstrating that the two magma batches cannot have mixed, implying a physical barrier between them. The available data do not rule out the possibility that deeper and hotter sections of the two magma systems mixed freely. (c) From 1.2 to 1.1 Ma there is rapid formation of two more batches of high-silica magma (>300 km³) following a major disruption of the stratified magma chamber(s). Magmas in the two pre-existing roof zones are not subsequently sampled during formation of the younger Glass Mountain lava domes. The presence of minerals from the older Glass Mountain lavas in the early formed Bishop Tuff implies that feldspars from the older Glass Mountain magmas were mixed into parts of the upper section of the new magma chamber(s). (d) The Long Valley magma chamber is partially emptied at 0.76 Ma during eruption of ~800 km³ of the Bishop Tuff and collapse of the Long Valley Caldera. Early airfall tuffs and ignimbrites (up to 500 km³; Hildreth, 1979; Wilson and Hildreth, 1997) contain mineral grains from both old and young Glass Mountain magmas whereas later eruptions, that have higher temperature magmatic material, only contain mineral grains from the young Glass Mountain magma system.

1994) but only provides constraints as to the volume of magma produced at the uppermost part of the magma system.

The Nd-Sr isotope systematics presented above (Fig. 4) and previous Sr and Ar isotope studies of the Bishop Tuff establish that the early Bishop Tuff contains feldspars and quartz of similar age and origin as the OGML. The late Bishop Tuff has the same Nd isotope systematics as the YGML and contains feldspars with similar Sr isotope systematics to those from the YGML. The Bishop Tuff was formed from ~800 km³ of erupted magma and the current data imply that a very large proportion of the phenocryst population was derived from magmas that produced the Glass Mountain Lavas. It is, however, important to remember that the entire magma chamber would not have been emptied during eruption of the Bishop

Tuff so again these volume estimates are minimum figures. The major unknown associated with this conclusion is the isotopic systematics of smaller mineral grains. So far only the largest grains have been subjected to isotopic analysis. As discussed above, the euhedral and unbroken nature of the vast majority of the phenocryst phases implies that these phenocrysts were derived from a magma rather than solid rock. It is therefore possible that the majority of the Bishop Tuff magma was produced by a series of four rapid differentiation events that are now recorded by the four regional isochrons of the Glass Mountain lavas. Placing exact estimates of the magma volumes involved in each magma production-differentiation event requires a detailed isotopic study of phases from throughout the Bishop Tuff. This is obviously impractical, but this work and

existing data suggest that material derived from the OGML was limited to the basal units of the Bishop Tuff (airfall and Ig1: Fig. 6, Halliday et al., 1984; Christensen and DePaolo, 1993; van den Bogaard and Schirnack, 1995; Christensen and Halliday, 1996). In contrast, the smaller Sr isotope disequilibrium between minerals and host glass recorded in the hotter (760 to 790°C), late Bishop Tuff units implies derivation from the YGML but with the addition of another magma immediately prior to eruption (Table 3; Halliday et al., 1984; Dunbar and Hervig, 1992; Christensen and Halliday, 1996). From the observed eruption volumes it is estimated that the early ~2.0 Ma differentiation events may have produced magma at a rate of up to $\sim 0.75 \times 10^{-2} \text{ km}^3/\text{yr}$ and that younger magmas were produced at a maximum of half this rate $0.4 \times 10^{-2} \text{ km}^3/\text{yr}$. These production rates only take account of volumes erupted by the Long Valley system and significant magma volumes were undoubtedly preserved in the fossil magma chamber after eruption of the Bishop Tuff (e.g., see Heumann and Davies, 1997). The conclusion reached in this and other recent studies (Halliday et al., 1989; Davies et al., 1994; Heumann and Davies, 1997; Reid et al., 1997) that silicic magmas are produced episodically, implies that previous estimates of silicic magma production rates, which were based on time integrated eruptive volumes in long-lived systems, will be too low (10^{-2} to $10^{-4} \text{ km}^3/\text{yr}$ with a mean of $10^{-3} \text{ km}^3/\text{yr}$; Smith, 1979; Spera and Crisp, 1981). Actual production rates will be at the higher end of these estimates and probably more comparable to basaltic systems than previously realized (e.g., $10^{-2} \text{ km}^3/\text{yr}$; Shaw, 1985). This conclusion may in turn imply that melt extraction from crustal sources also must be rapid and provides further support to workers who argue that granitic melts *s.l.* can be rapidly extracted from their source region (e.g., Petford et al., 1993; Sawyer, 1994).

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